Stellar and Primordial Nucleosynthesis of ^{7}Be: Measurement of ^{3}He$(\alpha, \gamma)^7$Be

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The ^{3}He$(\alpha, \gamma)^7$Be reaction presently represents the largest nuclear uncertainty in the predicted solar neutrino flux and has important implications on the big bang nucleosynthesis, i.e., the production of primordial ^{7}Li. We present here the results of an experiment using the recoil separator ERNA (European Recoil separator for Nuclear Astrophysics) to detect directly the ^{7}Be ejectiles. In addition, off-beam activation and coincidence γ-ray measurements were performed at selected energies. At energies above 1 MeV a large discrepancy compared to previous results is observed both in the absolute value and in the energy dependence of the cross section. Based on the available data and models, a robust estimate of the cross section at the astrophysical relevant energies is proposed.

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The ^{3}He$(\alpha, \gamma)^7$Be reaction is presently the largest nuclear uncertainty in the prediction of the solar neutrino flux and was considered as a possible key to solve the solar neutrino puzzle. The successful experiments of SNO [1] and Kamland [2] provided proof for the existence of neutrino oscillations and gave an explanation of the observed solar neutrino deficit in neutrino detectors on our planet. The data opened a new era of neutrino spectroscopy, in which the solar neutrino fluxes serve as a probe for details of the standard model of particle physics. In addition, the precise knowledge of the different neutrino fluxes can be used to understand physical and chemical properties of the Sun, provided that nuclear reaction cross sections are known with adequate accuracy. It appears possible to exploit neutrinos from the CNO-cycle and the pp-chain to determine the primordial solar core abundances of C and N [3], if the uncertainties in nuclear cross sections, neutrino observations and neutrino oscillation parameters can be significantly reduced. In the case of the cross section $\sigma(E)$ of ^{3}He$(\alpha, \gamma)^7$Be, which determines the flux of the recently detected ^{7}Be neutrinos [4], a precision of at least 3% should be achieved [3,5].

The ^{3}He$(\alpha, \gamma)^7$Be reaction also has important implications on big bang nucleosynthesis (BBN). A detailed comparison of the abundances of the primordial elements (D, ^{3}He, ^{4}He, ^{7}Li) predicted by the cosmological models based on the results of the Wilkinson Microwave Anisotropy Probe (WMAP) [6] with astronomical observations demonstrate a good agreement for the D and ^{4}He abundances. However, the predicted abundance of ^{7}Li is a factor 2 to 3 larger than observation, see e.g., [7,8]. According to standard model BBN, the ^{7}Li nuclei synthesized during the BBN were instantly destroyed due to the large cross section of ^{7}Li$(p, \alpha)\alpha$. The half-life of the electron capture of ^{7}Be produced by ^{3}He$(\alpha, \gamma)^7$Be is long enough that ^{7}Be survived until the proton density and energy is low enough to freeze out the ^{7}Li abundance. Therefore, an accurate evaluation of $\sigma(E)$ is the necessary basis for possible solutions of the ^{7}Li problem.

During the last four decades, many efforts have been devoted to the determination of $\sigma(E)$ at the relevant energies for BBN and stellar core hydrogen burning. All experiments exploited either the detection of the prompt γ rays [9–13] or the off-beam determination of the ^{7}Be atoms collected in the target [14–18], while in a few cases both techniques were used [19–21]. These experiments covered the energy range of BBN [$E \approx 180$ to 400 keV (Energies are in the center-of-mass system, except where differently quoted.)], while the Gamow energy in the Sun ($E_0 = 22$ keV) was not reached and models have to be used to extrapolate the data. The results show an overall fair agreement in the energy dependence of $\sigma(E)$, while they disagree in their absolute values. Nonradiative transitions have been suggested as a possible source of the observed discrepancy [22]. Recent measurements provided no evidence for such transitions [16,20,21], confirming theoretical expectations [23]. However, a global analysis of these results [24] shows that discrepancies are still present. These discrepancies result in an overall uncertainty of 7.4%, while the single determinations are affected by an error of about 3% or less. Finally, one should note that at energies above 1 MeV there exists essentially only one data set [9]. These data have a large influence on the determination of $\sigma(E_0)$, since they provide a strong test of the adopted model and, thus, determine the energy dependence in the extrapolation. Therefore, new data are needed aiming at a precise and accurate determination of $\sigma(E)$ at energies up to at least $E = 2$ MeV. This information is important to discriminate and constrain existing models, that are supposed to be valid up to this energy.

We present the results of a new approach, where $\sigma(E)$ was determined by the direct detection of the ^{7}Be recoils using the recoil separator ERNA at the Dynamitron Tandem Laboratorium of Ruhr-Universität Bochum, Germany. Concurrently, the capture γ rays were detected in coincidence with the recoils at selected energies, thus allowing a direct comparison of σ with the cross section for radiative transition σ_γ. The details of the experimental setup and procedures are reported in [25] and references therein.

In the energy range of the experiment, the recoil yield for each significant charge state q was measured in separate runs. The probability of forming neutrals in the target is negligible, since the target thickness ($N_{^3\mathrm{He}} = (2.00 \pm 0.08) \times 10^{17}$ atoms/cm^2) is too small to reach equilibrium, in which case a probability of less than 4% is expected at the lowest energy [26]. The associated uncertainty is negligible compared to the statistical error. Thus, $\sigma(E_{\mathrm{eff}})$ at the effective interaction energy E_{eff} is given by the relation:

$$\sigma(E_{\mathrm{eff}}) = \sum_q \frac{N_{^7\mathrm{Be},q}}{N_{^4\mathrm{He},q} T} \frac{1}{N_{^3\mathrm{He}} \epsilon_{^7\mathrm{Be}}}, \qquad (1)$$

where $N_{^4\mathrm{He},q}$, $N_{^7\mathrm{Be},q}$, and $\epsilon_{^7\mathrm{Be}}$ are the number of projectiles impinging on the target, the number of recoils collected in the end detector and the detection efficiency of the final detector, respectively. The transmission T of the recoils from the target to the end detector turned out to be sufficient for the full acceptance independent of the selected charge state [25]. The total beam energy loss in the target is small (i.e., $\Delta E < 2$ keV) and the cross section can be assumed constant over the target thickness. As a consequence, the effective interaction energy is given by $E_{\mathrm{eff}} = E_{\mathrm{in}} - \Delta E/2$, where E_{in} is the energy corresponding to the initial beam energy. The beam power dissipated in the target was of the order of a few mW, i.e., 2 orders of magnitude lower than in the measurement in [27], where no significant beam heating effect was found.

The determination of σ is affected by a systematic uncertainty of 5%, due to the uncertainties on T (1.0% at $E \geq 1$ MeV, 2.0% at $E < 1$ MeV), $N_{^3\mathrm{He}}$ (4%), $\epsilon_{^7\mathrm{Be}}$ (0.6% at $E \geq 1$ MeV, 1.7% at $E < 1$ MeV), and $N_{^4\mathrm{He}}$ (1%). For the ratio of σ_γ to σ, the following expression holds:

$$\frac{\sigma_\gamma(E_{\mathrm{eff}})}{\sigma(E_{\mathrm{eff}})} = \frac{\sum_q N_{\gamma,q}/N_{^4\mathrm{He},q}}{\sum_q N_{^7\mathrm{Be},q}/N_{^4\mathrm{He},q}} \frac{N_{^3\mathrm{He}}}{\int N_{^3\mathrm{He}}(z)\epsilon_\gamma(z)dz}, \qquad (2)$$

where $N_{\gamma,q}$ is the number of γ rays detected in coincidence with $N_{^7\mathrm{Be},q}$ recoils for the selected charge state q, while $\epsilon_\gamma(z)$ and $N_{^3\mathrm{He}}(z)$ represent the γ-ray detection efficiency and the target number density as a function of the reaction coordinate z along the target, respectively. The ratio σ_γ/σ is affected by a 5% systematic uncertainty, dominated by the γ-ray detection efficiency [25], and can be used to determine σ_γ once σ is known. Hence, the two determinations are not statistically independent.

In addition, measurements were performed to obtain cross section values independent of the recoil separator. The details of that experiment will be given elsewhere [28]. Briefly, a circular copper catcher ($\phi = 70$ mm) was installed at a distance of 31 cm from the gas target center to collect the produced ^{7}Be nuclei, where 99% of the recoils are distributed over a circle of 14 mm diameter at the lowest energy. The measurements were done at $E = 650$, 1103 and 2504 keV, where the probability of backscattering and sputtering is negligible. The ^{4}He beam current was of the order of 2 μA. The activity of the ^{7}Be nuclei was determined with the same setup as in [18] in the Low-Level Laboratory of the Laboratori Nazionali del Gran Sasso, Italy. Possible contributions of contaminant reactions to the observed ^{7}Be yield were investigated in background runs using ^{4}He instead of ^{3}He as the target gas. The normalization error of the activation is 5%, due to the uncertainties in the gas target thickness and the beam current integration, that are in common with the recoil and γ-ray data, and in the efficiency calibration of the detection setup (1.8%) [18]. In all three approaches, statistical errors are determined by the counting statistics and the current normalization (typically 1%).

The total cross section was measured in the energy range $E = 700$–3200 keV, while 6 γ-ray coincidence measurements were performed at energies between $E = 1100$ and 3000 keV. Sample identification matrices and gamma-ray spectra are shown in [25]. The results are plotted in the form of the astrophysical S factor ($S(E) = E\sigma(E) \times \exp(31.29 \cdot 4\sqrt{1.720/E})$, E in keV) in Fig. 1 and compared with the results of previous work in the overlapping energy range. It is worth noting that the resonance corresponding

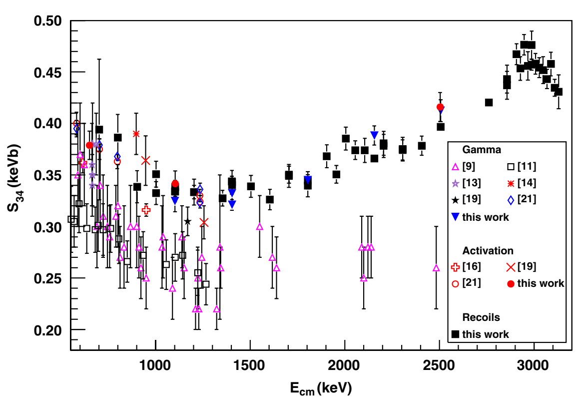

FIG. 1 (color online). Results of the cross section measurements of the present work. The data are plotted in the form of the astrophysical S factor as a function of the center-of-mass effective interaction energy. The results of previous work in the same energy range are also shown.

to the $J^\pi = 7/2^-$, $E_x = 4570$ keV state in ^{7}Be was observed for the first time in this reaction. The experimental resonance strength is $\omega\gamma = 0.33 \pm 0.21$ eV, with $\Gamma = (2.1 \pm 1.0) \times 10^2$ keV. This corresponds to $B(E2) = 52 \pm 31 e^2$ fm^4, assuming a pure ground state transition for the resonance; a shell-model estimate including core polarization effects gives $B(E2) = 12 e^2$ fm^4 [29].

The influence of different γ-ray angular distributions on the determination of σ_γ, i.e., from [30] and isotropy, was studied with a GEANT4 simulation of the detection setup. Differences were found to be negligible and, therefore, an isotropic angular distribution was adopted. This distribution describes fairly well the observed relative yields in the different detectors at energies lower than $E = 2500$ keV, while at higher energies significant deviations were observed. Since the angular information provided by our γ-ray detector setup is insufficient to fix the parameters of the angular distributions, these data points were excluded from the analysis. Finally, the results of the activation measurements are also shown. All three methods agree within their uncertainties and confirm that there is no evidence of nonradiative transitions ($\sigma_\gamma/\sigma = 0.99 \pm 0.05$). Table I summarizes the numerical values of the results, including the experimental intensity ratio $R = \sigma_{429}/\sigma_{\rm gs}$, that are plotted and compared with previous results in Fig. 2.

In the comparison with previous works, there is a significant discrepancy of both the absolute scale and the energy dependence of the S factor from the results of [9]. It is worth noting that the cascade-to-ground state intensity ratio in [9], as shown in Fig. 2, deviates significantly from all other determinations, including the present data. The origin of this discrepancy is difficult to identify, but might influence the determination of the cross section. An excellent agreement is found with the determination of [19] and the recent measurement of [21]. In regard to [16], the agreement is only within 2σ. Even larger is the discrepancy with [11]: one should note, however, that those data needed a renormalization [13] and thus they do not provide independent information on the absolute scale.

The comparison with the remaining data sets is more complex, since it must be done through model calculations. Table II summarizes the results of fits of different models [31–36] to data sets of the present work and [16–18,20,21]. This selection considers the more recent experiments, where higher accuracy and precision of the data is claimed. The results are presented at $E = 0$, as is usually done in literature. The more significant fits are shown in Fig. 3. The least square fits to the data sets were obtained by scaling each model calculation by a constant factor k. This procedure is somewhat questionable for microscopic models, but the possible inaccuracy resulting from the scaling stays small when $k \approx 1$. The quoted uncertainties were evaluated following the Monte Carlo procedure described in [37], including both statistical and normalization errors. The direct capture model of [32] does not provide a good

TABLE I. Numerical values of the measurements performed in the present work. The quoted uncertainties are statistical only. Systematic uncertainties are 5% for recoils, 7% for γ ray, and 5% for activation measurements. These uncertainties include the contribution of target thickness (4%) and current integration (1%), that are common to all measurements. See text for details.

Recoils		Recoils	
$E_{\rm eff}$ (keV)	σ (μb)	$E_{\rm eff}$ (keV)	σ (μb)
701	1.14(20)	2105	4.96(16)
802	1.46(8)	2156	4.95(5)[a]
902	1.59(7)	2205	5.24(16)
1002	1.96(7)	2205	5.20(16)
1002	1.86(6)	2305	5.32(14)
1102	2.16(2)[a]	2306	5.33(16)
1102	2.19(4)	2406	5.54(14)
1103	2.16(6)	2507	5.97(6)[a]
1203	2.44(5)	2762	6.70(7)
1203	2.44(9)	2857	7.2(4)
1353	2.79(7)	2857	7.1(4)
1403	3.06(4)[a]	2908	7.7(3)
1403	3.03(8)[a]	2928	7.5(4)
1403	3.06(10)	2947	7.9(3)
1504	3.27(10)	2968	7.6(5)
1604	3.37(10)	2987	7.59(9)
1704	3.84(12)	2988	7.9(5)
1704	3.86(9)	3008	7.6(3)
1804	4.01(4)[a]	3028	7.6(3)
1804	3.95(12)	3048	7.6(4)
1904	4.49(14)	3068	7.5(3)
1955	4.38(11)	3089	7.7(4)
2005	4.92(14)	3110	7.4(3)
2055	4.87(12)	3130	7.3(6)

Activation	
$E_{\rm eff}$ (keV)	σ (μb)
650	0.95(11)
1103	2.23(10)
2504	6.0(4)

Gamma rays	
$E_{\rm eff}$ (keV)	σ (μb)
1102	2.10(7)
1403	2.96(8)
1403	2.86(5)
1804	4.01(10)
2156	5.25(13)
2507	6.20(16)

Intensity ratio	
$E_{\rm eff}$ (keV)	R
1102	0.47(3)
1403	0.45(2)
1403	0.458(13)
1804	0.453(19)
2156	0.403(16)
2507	0.428(18)

[a]Measurements where coincidence γ rays were detected.

description of the observed energy dependence of the S factor above 1 MeV, where it is supposed to still be accurate. A better result is obtained using microscopic models, e.g. [31,33–36]. In particular, good results are

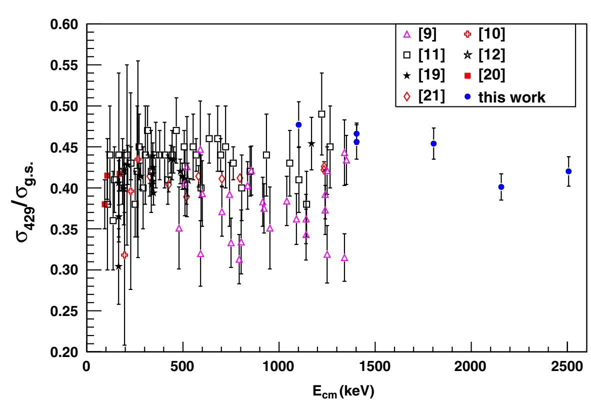

FIG. 2 (color online). Ratio of the cascade-to-ground state transition intensities measured in this work as a function of the center-of-mass energy, compared to previous measurements.

TABLE II. Determination of $S_{34}(0)$ using different data sets and models. Uncertainties include both normalization and statistical errors.

Model	this work and [21]			[16–18,20]			All		
		$\nu = 39$			$\nu = 13$			$\nu = 53$	
	k	$S_{34}(0)$ (keV b)	χ^2	k	$S_{34}(0)$ (keV b)	χ^2	k	$S_{34}(0)$ (keV b)	χ^2
[31]	0.93	0.65(2)	55	0.81	0.568(12)	20	0.89	0.628(14)	456
[32]	1.22	0.62(2)	188	1.09	0.553(11)	11.4	1.19	0.605(13)	485
[33]	1.17	0.60(2)	56	1.09	0.555(11)	14.5	1.15	0.588(13)	189
[34]	0.86	0.527(15)	74	0.84	0.512(11)	46	0.86	0.523(12)	137
[35]	1.03	0.516(14)	93	1.00	0.497(10)	49	1.02	0.512(11)	169
[36]	1.47	0.590(16)	41	1.37	0.552(11)	14.1	1.45	0.581(13)	153

obtained considering two subsets of data, as given in Table II.

In conclusion, our data in combination with the measurements of [21] give a best estimate of $S_{34}(0) = 0.590 \pm 0.016$ keV $\cdot$ b using the model in [36], although one should be aware of the possible inaccuracy due to the large scaling needed to fit the data. An alternative determination of $S_{34}(0) = 0.553 \pm 0.012$ keV $\cdot$ b using the models in [32,33,36] with the data in [16–18,20] cannot be ruled out. Until new information is available to assess which is the correct determination, a conservative estimate of $S_{34}(0) = 0.57 \pm 0.04$ keV $\cdot$ b is suggested. This estimate represents an improvement with respect to the recommendation of [38], but it is still far from the precision required by solar models.

A primordial ^{7}Li abundance $^7\mathrm{Li/H} = (5.4 \pm 0.3) \times 10^{-10}$ is obtained using this conservative $S34(0)$ value in the BBN code of [39] with the WMAP determination for the baryon fraction $\Omega_b h^2 = 0.02273 \pm 0.00062$. The quoted uncertainty on ^{7}Li/H takes into account all relevant nuclear processes involved in ^{7}Li and ^{7}Be production or destruction. This theoretical determination is larger than the observational value by a factor 3 or more, see e.g. [8], thus worsening the primordial ^{7}Li problem.

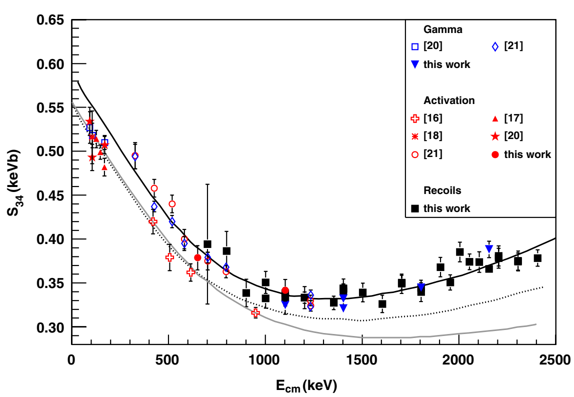

FIG. 3 (color online). Comparison of the results of the data of the present experiment and recent works with different model calculations fitted at $E \leq 2000$ keV, see text for details. Data of the present work and [21]: solid black line [36]. Data of [16–18,20]: solid grey line [32], dotted line [33].

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